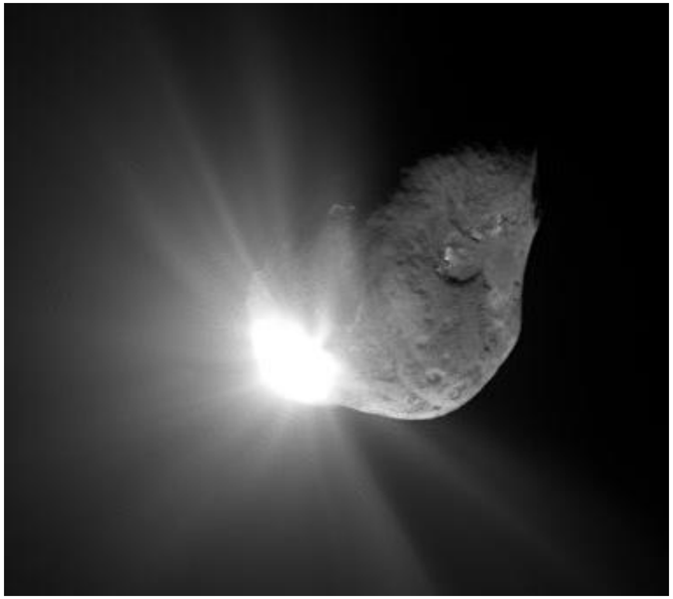
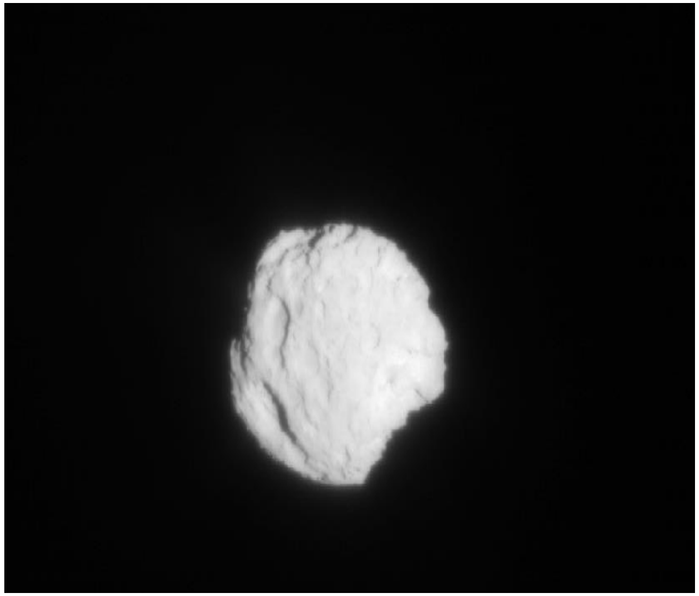
Autonomous Navigation Across the Solar System





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Background on Deep Space Navigation

- Spacecraft have visited 8 planets, 3 dwarf planets (Vesta, Ceres, Pluto), asteroids and comets
- Deep space navigation (beyond cis-lunar space) different from Earth vicinity navigation – no GPS available
- For deep space, tracking data are received using one of three Deep Space Network complexes (Goldstone, CA, Canberra, Australia, and Madrid, Spain)
- Tracking data includes:
  - 2-way Doppler, which measures line-of-sight velocity from spacecraft to tracking station
  - 2-way range, which measures line-of-sight range from spacecraft to tracking station
  - Delta-Differential One-way Range (Delta-DOR), which provides plane-of-sky angular measurement
  - Optical images of natural bodies taken by onboard camera (OpNav), which measures angle between spacecraft and body against an inertial reference

Background on Deep Space Navigation

- Unlike GPS, data does not have the geometry to provide instantaneous kinematic position fixes
- Data must be processed and combined with dynamical models to estimate spacecraft trajectory
  - For most missions and mission phases, Doppler, range and DDOR sufficient to satisfy mission requirements
  - In cases where target body ephemeris is not known with sufficient accuracy (asteroids and comets, outer planets, planetary satellites), optical data provides powerful target relative information needed to successfully navigate the mission
  - Optical data typically used as spacecraft approaches target body
  - Optical data also critical for proximity operations around small body
- Current capabilities can achieve highly accurate results, for example:
  - Sub-km level targeting accuracies for satellite flybys on Cassini mission
  - 10s of km landing ellipses on Mars
- Still need to keep increasing performance for future missions, and alleviate pressure on DSN use

Drawbacks to Ground-based Navigation

- Long round-trip light time (many minutes to many hours), depending on where the spacecraft is in Solar System
- Time needed to process the data by analysts
  - Orbit determination and maneuver calculations
  - Analyze results
  - Convene meetings to make decisions and implement decisions
  - Generate sequence commands and uplink them to spacecraft
- Lag time between the last navigation update and implementing maneuvers can typically take 8 or more hours to over a week. As a result:
  - Loss of some science, for example, to precisely point instruments at a target cannot use latest navigation knowledge
  - Loss for mission parameters, such as increased use of fuel as the orbit information has become stale during turnaround time to implement maneuvers

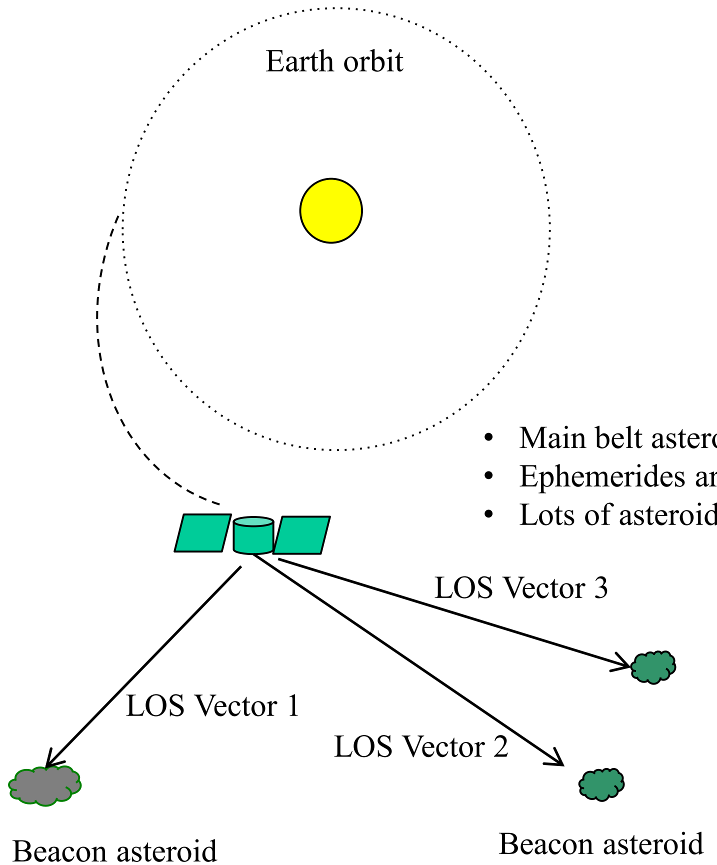
Onboard Autonomous Navigation

- A self-contained, onboard, autonomous navigation system can:
  - Eliminate delays due to round-trip light time
  - Eliminate the human factors in ground-based processing
  - Reduce turnaround time from navigation update to minutes, down to seconds
  - React to late-breaking data
- A framework and computational elements of an autonomous navigation system has been developed, called AutoNav
  - Originally developed as one of the technologies for the Deep Space 1 mission, launched in 1998
  - Subsequently used on three other spacecraft, for four different missions
  - Primary use has been on comet missions to track comets during flybys, and impact one comet

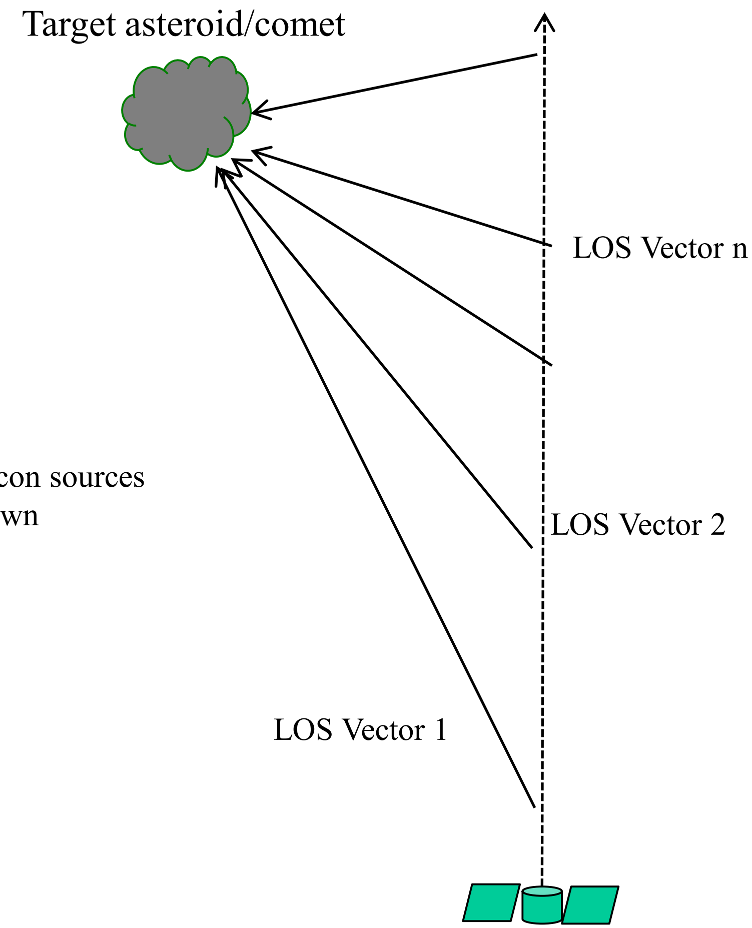
AutoNav Data

- In principle, can use same data as ground-based navigation (radiometric and optical)
  - Radiometric data requires other information, such as media calibrations, for Earth-based data, or location of other spacecraft for spacecraft-to-spacecraft data
- More straightforward to use entirely self-contained data, so current AutoNav based on using optical data only (OpNav)
  - Passive optical data uses onboard camera to image celestial bodies
  - Bodies can be distant point sources ("unresolved"), distant resolved bodies, or bodies which partially or completely fill the camera FOV, in which case terrain-relative navigation techniques can be employed
- AutoNav system being further enhanced to incorporate additional data types, including Doppler, range, LIDAR, etc.
- Current work involves quantifying navigation accuracies using optical data alone and combined with one-way Doppler and/or range, for use across the Solar System

AutoNav Concept



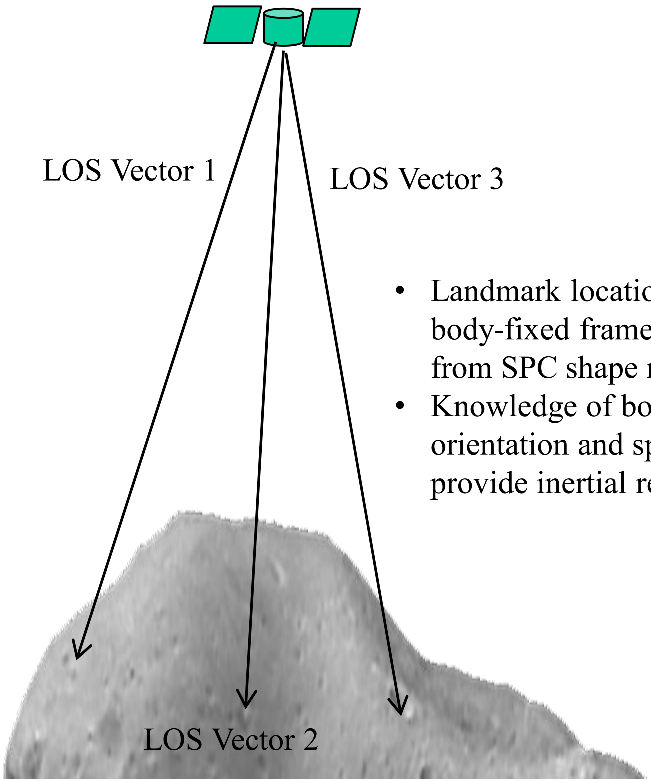
- Main belt asteroids provide good beacon sources
- Ephemerides are reasonably well known
- Lots of asteroids to chose from



Interplanetary cruise scenario
Technique used on DS1

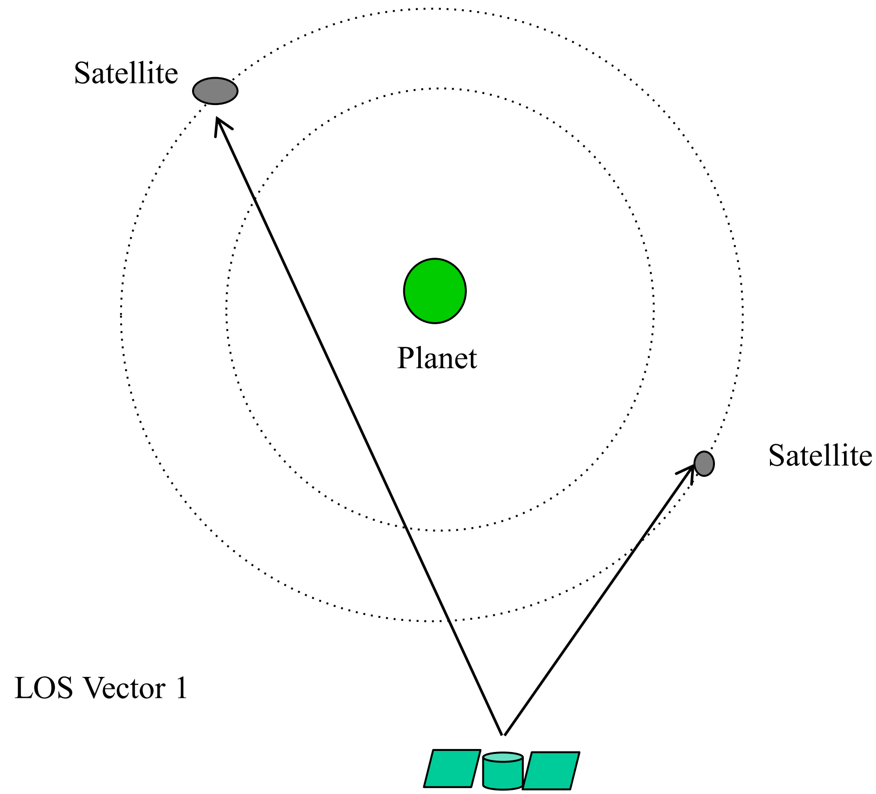
Small body flyby scenario
Technique used on DS1, Stardust, DI

AutoNav Concept



- Landmark locations in body-fixed frame known from SPC shape model
- Knowledge of bodies pole orientation and spin rate provide inertial reference

Small body orbiting and/or landing scenario

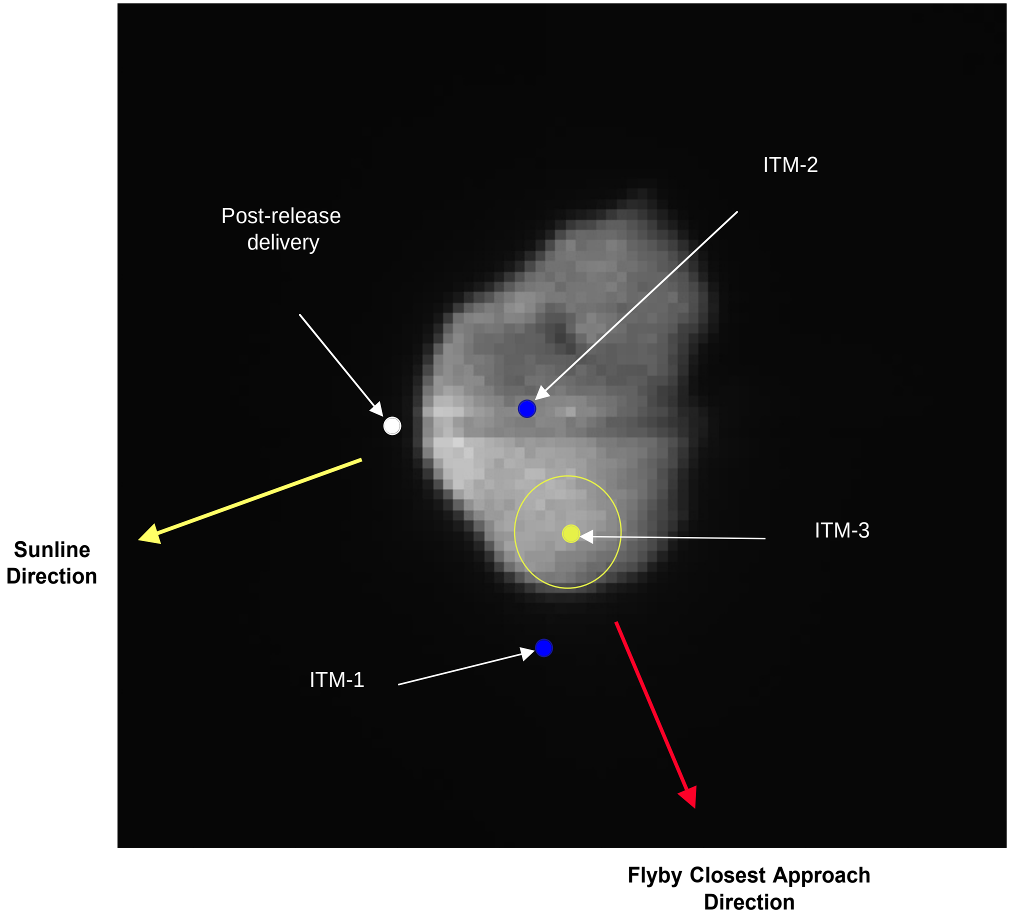


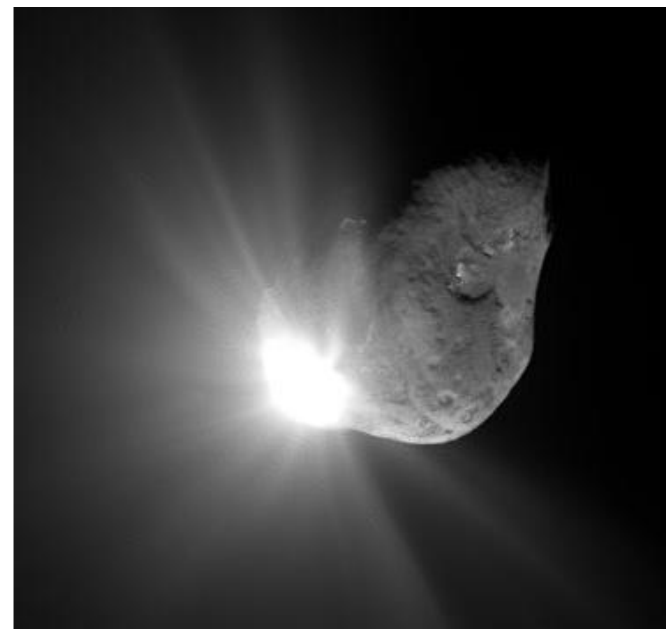
Approach and/or tour of planetary system containing satellites

Mission Results

- 5 missions using 4 different spacecraft have used AutoNav during the mission
  - Deep Space 1 (cruise and flyby of comet Borrelly)
  - Stardust (flyby of asteroid Annefrank and comet Wild 2)
  - Deep Impact (Impactor and Flyby spacecraft imaging for comet Tempel 1)
  - EPOXI (flyby of comet Hartley 2)
  - Stardust NExT (flyby of comet Tempel 1)
- Flyby mission parameters

Mission/Target	Flyby Radius (km)	Flyby Velocity (km/s)	Approach Phase (deg)
DS1/Borrelly	2171	16.6	65
STARDUST/Annefrank	3076	7.2	150
STARDUST/Wild 2	237	6.1	72
DI/Tempel 1	500/0	10.2	62
EPOXI/Hartley 2	694	12.3	86
STARDUST NExT/Tempel 1	182	10.9	82


ITM-2
Post-release
delivery
Sunline
Direction
ITM-3
ITM-1
Flyby Closest Approach
Direction



EPOXI and Stardust NExT

AutoNav Error Sources

- Inertial direction of LOS vectors
  - If stars are not in camera FOV, then inertial pointing of camera boresight will be a large error source and must be estimated in the filter.
- Observed target/landmark inertial location
  - For distant beacon asteroids, error in their ephemeris will corrupt s/c location estimation. Similarly, errors in the locations of landmarks will also corrupt the estimate
  - For purely target-centered flybys where the s/c inertial location in space is not relevant, this is not an issue
- Spacecraft non-gravitational forces
  - Onboard estimates all s/c non-grav forces (maneuvers, momentum wheel desaturations, attitude control firings) from IMUs is typically not very accurate
- Centerfinding ability
  - Mismodeling of point source point spread, smearing due to exposure duration, ability to pinpoint landmark

Current Status

- Looking at mapping the "GDOP" capability of all-optical system across the Solar System
- Wide variety of mission scenarios being considered
  - Interplanetary cruise through inner and outer Solar System
  - Planetary approach and orbit insertion, for planets with and without natural satellites
  - Satellite tours (e.g., Cassini, Europa Orbiter type missions)
  - Small body approach, proximity operations, and landings
- System architecture studies
  - Camera hardware requirements
  - Effect of uncertainties in ephemerides of natural bodies used as beacons
- Comparison between all-optical system vs standard ground-based navigation in terms of various metrics
  - Propellant requirements
  - DSN tracking needs
- Assessing impact of the addition of one-way radiometric data

Potential Future Uses of AutoNav

- Planetary defense
  - Asteroid deflection – terminal guidance for high speed impact already demonstrated. Enhancements would allow for greater variability in approach velocity and target sizes
  - Gravity tractoring – maintaining hover location using low-thrust to pull asteroid using s/c gravity
- Small body/Lunar pinpoint landing – numerical simulations indicate AutoNav capable of delivering lander to less than 3 m accuracies for small bodies and 20 m for the moon
- Outer planet satellite tour – rapid turnaround navigation could take advantage of delta-v and mission time savings in complex dynamical environment
- CubeSat, NanoSats, etc. – multiple, small s/c exploration of solar system would severely tax DSN assets. Some type of AutoNav required to reduce navigation tracking time

Investments in Technology Needed for Future AutoNav

- Gimbal mounted cameras
  - Would reduce need to slew entire s/c to image objects. Allows for separation of s/c attitude maintenance and need for pointing
- Miniaturization of camera systems
  - Smaller cameras for lower mass, needed for notional CubeSats or other small s/c.
  - Small aperture limitation for getting enough signal-to-noise for proper image processing
- Enhanced image processing techniques
  - Would reduce/eliminate false detections and centroiding errors
- Potential addition of other data types
  - Lidar, radar altimetry
  - One-way radiometric from the Earth or space assets (e.g. using DSAC for timing and IRIS radio)

Investments in Technology Needed for Future AutoNav

- “AutoNav in a box” would:
  - Provide single piece of hardware that combines narrow-angle camera for navigation with wide-angle camera and IMUs for attitude control, and processor for AutoNav computations (e.g., DPS system)
  - Provide GPS-like functionality for most deep space applications (cruise, approach, orbit and landing)
- Combination of AutoNav with AI enabled spacecraft would enable more autonomous spacecraft that can make decisions on its own